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13. ABSTRACT *(Maximum 200 Words)*

Theoretical studies have been made on the nonlinear operating regimes of crossed-field vacuum devices, in the nonrelativistic regime. The main interaction is a wave-particle interaction between those drifting electrons whose velocities match the phase velocity of the RF wave in the slow-wave structure. The theory is based on two elementary modes: a DC average background mode and an RF oscillating mode. These elementary modes interact nonlinearly via a nonlinear diffusion process, for which there are sometimes stationary equilibrium states. When these stationary states do exist, the operating characteristics of the modes have been detailed, and criteria for determining the operating parameter regimes have been given. This work suggested that such devices should not operate at more than about 20% above the Hartree voltage, due to the parametric generation of intense subharmonic modes, at voltages higher than this. The work also found that whenever a cyclotron resonance did occur inside the plasma region, the growth rate would essentially vanish. Thus such regimes should be avoided since the amplification would be weak, at best.

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THEORETICAL STUDIES IN CROSSED-FIELD DEVICES
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OBJECTIVES

1. Identify the basic processes involved in the initialization of the operating mode for crossed-field devices.
2. Identify/describe the electron sheath modifications produced upon device activation.
3. Identify the various nonlinear operating modes of the device.

RESULTS OF RESEARCH

The above objectives have been achieved. We have determined that we do have a means of estimating the operating regime of crossed-field devices. In published papers, we have demonstrated that one may model the plasma inside a magnetron or a crossed-field amplifier (CFA) with two modes: a DC stationary background, and an oscillating RF mode. Initially, in the absence of any RF mode, the device may be in a quiescent state, (if such would be stable) with the plasma in a classical Brillouin flow. As the RF wave is injected into the slow-wave structure (for a CFA) or grows from the background noise (for a magnetron), nothing significantly happens unless there is a wave-particle (diocotron) interaction at the edge of the Brillouin sheath. In this interaction, the drifting electrons move with the phase velocity of the RF wave in the slow-wave structure. Consequently, these electrons will be continually accelerated, causing them to readjust their positions and undergo a nonlinear diffusion, until a new background equilibrium is achieved between the propagating RF wave and the drifting electrons. This new equilibrium has a nonBrillouin density profile, and is called a stationary operating density profile. These density profiles are typically nonzero thoughout the region between the cathode and anode, have a negative density gradient, and must be nonzero at the anode. (The latter is our latest result, and a publication is in preparation on the description of this result.) The nonzero value of the plasma density at the anode, N_{0a}, is determined by the intensity of the RF field in the slow-wave structure. As the RF field propagates down the slow-wave structure and grows, it drives the the value of N_{0a}. If the RF field intensity becomes too large, then N_{0a} is driven to become too large, and a period–doubling instability can result. There are also other possible instabilities that may result. Further work will be required to detail them and how they may possibly relate to known device operating characteristics.

We have also demonstrated why such devices usually do not operate more than about 20% above the Hartree voltage. The reason is that above this limit, the parametric interactions start to produce broad-band subharmonic modes, which could then take over and dominate the device. In the process of obtaining these results, we also have obtained comprehensive diagrams and plots of the dispersion characteristics and parametric interactions in various parameter regimes. These are still to be sorted through and studied for additional implications.

One important consideration for relativistic devices, is that we have consistently observed that if any cyclotron resonances occur inside the plasma, the growth rate virtually vanishes. This suggests that one should design these devices so that neither of the cyclotron resonances occur inside the plasma region. However, to design for this, one would need to know the stationary operating density profile for the relativistic case. In this direction, we have obtained the model equations for the planar model of the relativistic case, which would be required for these studies.

We have also done important work on three-wave resonant interactions, dispersion managed solitons, gap solitons, second-harmonic generation, and a new type of soliton (embedded soliton). All these items contain results that can be related to interactions inside a crossed-field device.

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  + Prof. E. Ibragimov (Mich. Tech. Univ., parametric interactions)
  + Prof. Boris Malomed (Tel Aviv Univ., nonlinear interactions)
  + Dr. Heinz Steudel (Max-Planck, Berlin, nonlinear interactions)
  + Prof. Jianke Yang (Univ. of Vermont, developer of our cold-fluid code.)
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PUBLICATIONS

* SUBMITTED

* Journals
  + *Inverse scattering method applied to degenerate two–photon propagation in the low excitation limit*, H. Steudel and D.J. Kaup, (submitted to J. Physics A).

* Conferences

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* Journals
  + *Excitation of Upper–Hybrid Waves from O–Mode Electromagnetic Waves Via Density Gradient in the Ionosphere*, S. N. Antani, D.J. Kaup and N.N. Rao, J. Geophysical Research **101**, 27,035-041 (1996).
  + *Effective Control of a Soliton by the Sliding-Frequency Guided Filters*, S. Burtsev and D.J. Kaup, JOSAB **14**, 627-635 (1997).
  + *Asymptotic Behavior of N–Soliton Trains of the Nonlinear Schrödinger Equation*, V. S. Gerdjikov, D. J. Kaup, I. M. Uzunov and E. G. Evstatiev, Phys. Rev. Lett. **77**, 3943-6 (1996).
  + *Asymmetric Solitons in Mismatched Dual-Core Optical Fibers*, D.J. Kaup, T.I. Lakoba and Boris A. Malomed, JOSA B **14**, 1199-1206 (1997).
  + *Interactions between Polarized Soliton Pulses in Optical Fibers: Exact Solutions*, M. Karlsson, D. J. Kaup and B. A. Malomed, Phys. Rev. E **54**, 5802-8 (1996).
  + *Solitons in Nonlinear Fiber Couplers with two Orthogonal Polarizations*, T. I. Lakoba, D. J. Kaup and Boris A. Malomed. Phys. Rev. E **55**, 6107-20 (1997).
  + *Degenerate Two–Photon Propagation and the Oscillating Two–Stream Instability: General Solution for Amplitude-Modulated Pulses*, H. Steudel and D.J. Kaup, J. Mod. Optics **43**, 1851-66 (1996).
  + *Solutions of Degenerate Two–Photon Propagation from Bäcklund Transformations*, H. Steudel, R. Meinel and D.J. Kaup, J. Mod. Optics **44**, 287-303 (1997).
  + *Exactly Solvable 1D Model of Resonance Energy Transfer*, D. J. Kaup and V. I. Rupasov, J. Phys. A **29**, 2149-62 (1996).
  + *Exactly Solvable 3D Model of Resonance Energy Transfer*, D. J. Kaup and V. I Rupasov, J. Phys. A **29**, 6911-6923 (1996).
  + *Variational Principle for Cross-Field Devices*, D. J. Kaup and Gary E. Thomas, J. Plasma Physics **57**, 765-84 (1997).
  + *Initial Value Problem of the Linearized Benjamin-Ono Equation and Its Applications*, Y. Matsuno and D.J. Kaup, J. Math. Phys. **38**, 5198-224 (1997).

+ *Density Profiles and Current Flow in a Crossed–Field Amplifier*, D.J. Kaup and Gary E. Thomas, J. Plasma Phys. **58**, 145-61 (1997).
+ *Linear Stability of Multiple Internal Solitary Waves in Fluids of Great Depth*, Y. Matsuno and D. J. Kaup, Phys. Lett. A **228**, 176-181 (1997).
+ *Relativistic Density Profiles and Current Flow in a Crossed-Field Relativistic Electron Vacuum Device*, D.J. Kaup, T.I. Lakoba, and Gary E. Thomas, Proceedings of the 1997 SPIE Conference, Intense Microwave Pulses, Section V, 31 July-1 August, San Diego, CA, Vol. 3158, pp. 137-44 (1997).
+ *Stability of Solitons in Nonlinear Fiber Couplers with two Orthogonal Polarizations*, T. I. Lakoba and D. J. Kaup, Phys. Rev. E **56**, 4791-4802 (1997).
+ *Perturbation Theory for the Manakov Soliton and Its Application to Pulse Propagation in Randomly Birefringent Fibers*, D. J. Kaup and T. I. Lakoba, Phys. Rev. E **56**, 6147-65 (1997).
+ *Criterion and Regions of Stability for Quasi-Equidistant Soliton Trains*, V. S. Gerdjikov, E. G. Evstatiev, D. J. Kaup, G. L. Diankov, and I. M. Uzunov (To appear in the Proceeding of the 1997 NEEDS workshop, Crete, 22 June, 1997.)
+ *The N-Soliton Interactions, Complex Toda Chain and Stable Propagation of NLS Soliton Trains*, V. S. Gerdjikov, E. G. Evstatiev, D. J. Kaup, G. L. Diankov, and I. M. Uzunov. (To appear in the Proceedings of *Advanced Photonics with Second–Order Optically Nonlinear Processes*, NATO Advanced Study Institute, Sozopol, Bulgaria, 25 Sept., 1997.)
+ *The Inverse Scattering Transform for the Benjamin-Ono Equation*, D. J. Kaup and Y. Matsuno, Stud. Appl. Math. **101**, 73-98 (1998).
+ *Stationary Operating Density Profiles in a Crossed–Field Amplifier*, D.J. Kaup and Gary E. Thomas, J. Plasma Phys. **59**, 259-76 (1998).
+ *Conditions for Stationary Pulse Propagation in the Strong Dispersion Management Regime*, T. I. Lakoba, J.Yang, D. J. Kaup and B.A.Malomed, Optics Communications **149**, 366-75 (1998).
+ *Complete Integrability of the Benjamin-Ono Equation by Means of Action-Angle Variables*, D.J. Kaup, T.I. Lakoba and Y Matsuno, Physics Letters A **238**, 123-33 (1998).
+ *On the Shape of the Stationary Pulse in the Strong Dispersion Management Region*, T.I. Lakoba and D. J. Kaup, Electron. Lett. **34**, 1124-6 (1998).
+ *Gap Solitons in Asymmetric Dual–Core Nonlinear Optical Fibers*, D.J. Kaup and B.A. Malomed, JOSA B **15**, 2838-46 (1998).
+ *Stability and Quasi-Equidistant Propagation of NLS Soliton Trains*, V. S. Gerdjikov, E. G. Evstatiev, D. J. Kaup, G. L. Diankov, and I. M. Uzunov, Phys. Letters A **241**, 323-28 (1998).
+ *Hermite–Gaussian expansion for pulse propagation in strongly dispersion managed fibers*, T.I. Lakoba and D.J. Kaup, Phys. Rev. E **58**, 6728-41 (1998).
+ *Inter-Channel Pulse Collision in a Wavelength-Division-Multiplexed System with Strong Dispersion Management*, D.J. Kaup, B.A.Malomed, and J. Yang, Optics Letters **23**, 1600-02 (1998).
+ *Soliton Pulse Compression in the Theory of Optical Parametric Amplification*, E. Ibragimov, A. Struthers, and D.J. Kaup, Optics Comm., **152**, 101-7 (1998).
+ *Suppression of collision-induced pulse jitter in the WDM return-to-zero communications by strong dispersion management*, D.J. Kaup, B.A. Malomed, and J. Yang, Proceedings of SPIE, **3531**, 27-38, (1998).
+ *Density Profiles and Current Flow in a Crossed-Field, Electron Vacuum Device*, D.J. Kaup and G. E. Thomas, To appear in the proceedings of the 2nd International Conference on Crossed–Field Vacuum Devices, Boston, Mass., 17-18 June, 1998.
+ *Growth of Small Signal Noise in a Crossed-Field Electron Vacuum Device*, D. J. Kaup, J. O. El-Reedy, and Gary E. Thomas, Proceedings of SPIE AeroSense '99 **3702**, 57-67 (1999).
+ *Perturbation Theory for the Benjamin–Ono Equation*, with T.I. Lakoba and Y. Matsuno, Inverse Problems **15**, 215-240 (1999).
+ *Three-Wave Interaction Solitons in Optical Parametric Amplifcation*, E. Ibragimov, A. A. Struthers, D. J. Kaup, J. D. Khaydarov, and K. D. Singer, Phys. Rev. E **59**, 6122-37 (1999).
+ *Influence of the Raman Effect on Dispersion–Managed Solitons and Their Interchannel Collisions*, with T. I. Lakoba, Optics Letters **24**, 808-10 (1999).

+ *Solitary Waves in Perturbed Generalized Nonlinear Schrödinger Equations*, with Jianke Yang (To Appear in SIAM J Appl. Math.)
+ *Embedded solitons in second-harmonic-generating systems*, with J. Yang and B.A.Malomed (To Appear in Phys. Rev. Letters).
+ *Collision-induced pulse timing jitter in a WDM system with strong dispersion management* , with B.A. Malomed and J. Yang (To Appear in JOSA B).
+ *The Inverse Scattering Transform on a Finite Interval*, D.J. Kaup and H. Steudel. (To Appear in J. Physics A)